RESEARCH DEPARTMENT

Recent work on the effects of reflectors in concert halls and music studios

RESEARCH REPORT No. B-085

1965/18

THE BRITISH BROADCASTING CORPORATION
ENGINEERING DIVISION

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T. Somerville, B.Sc., M.I.E.E., F.Inst.P.,
C.L.S. Gilford, Ph.D., M.Sc., F.Inst.P., A.M.I.E.E.,
N.F. Spring, B.Sc., Grad.Inst.P., Grad.I.E.E.,
R.D.M. Negus, Grad.I.E.E.,

Head of Research Department

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SUMMARY

A common complaint in many modern concert halls is poor tonal quality. It has been suspected that this effect was due in large measure to the use of reflecting canopies and other large reflecting surfaces. Furthermore, vertical shifts in the apparent position of the sound source are often observed. This report describes experiments to investigate both these effects which are shown to be due to the use of directional reflexion.

1. INTRODUCTION

About 1945 after the end of the war, it became necessary for the BBC to consider the modernisation of studios which had not been refurbished for many years. Because of hostilities no large orchestral studios had been built since 1939 and a survey of the requirements was considered to be highly desirable.

In a large orchestral studio it is necessary to provide the conditions for performances which will simulate concert hall conditions as nearly as possible. Investigations were, therefore, made in a number of concert halls. In particular two halls were compared,[1] St. Andrew's Hall, Glasgow, the only remaining good concert hall of its period, since destroyed by fire, and Liverpool Philharmonic Hall, a modern hall completed in 1939.

Liverpool Philharmonic Hall is fan shaped and designed to direct sound from the orchestra to the audience, and in it were observed characteristics which have subsequently appeared in all modern halls in which the direction of sound has been practised Perhaps the most extreme example of the direction of sound occurs in the Royal Festival Hall which is noted for its short reverberation time and the shrill tonal quality which has become associated with all halls having efficient direction of sound on to the audience.

It is worth considering the reasons for the adoption of direction of sound in modern halls. It is argued that because a large number of seats is necessary for economic reasons and the volume is therefore large, the sound will not be loud enough at the rear, and reinforcement must be provided by reflecting sound from the orchestra towards the rear of the hall. The assumptions behind this technique are based on an investigation by Haas which was carried out at the University of Göttingen. Haas investigated the effect of delay between two sources of sound, which, in his case, were loudspeakers placed at an angle of 45 degrees on each side of the subject. He showed that the sound appeared to come from one loudspeaker which took 'precedence' over the other even when the amplitude in the other loudspeaker was greater, provided that the sound from the second loudspeaker was delayed. When the delay became too great, say greater than 50 m/s, the sound from the second loudspeaker appeared as an echo. These results of Haas have been widely employed in sound reinforcement systems. Haas, however, noted that even when the delays were short, the quality of the sound was different, although he considered that the change was beneficial. He also pointed out that if the delayed and undelayed sounds were radiated from the same loudspeaker serious distortion resulted from delays between 0 to 20 m/s.

Concert hall designers have assumed, without much justification, that the precedence effect which takes place in the horizontal plane would be equally applicable in the case of an orchestra and a reflexion from a canopy overhead. Observation shows this not to be the case, since it is frequently noticed in concert halls with large canopies that the sound from the orchestra appears to come from above the performers' heads.

When the post-war rebuilding of studios was started in 1949/50, it was decided not to use directional reflectors because the early observations made even before the Festival Hall was built indicated that such methods produced a shrill quality and a very patchy distribution of sound throughout the enclosure. Nothing in concert halls or orchestral studios built since that date has caused us to change our views, but the exact explanation of the effects to which we object have remained obscure until recently. It was decided, about a year ago, to find the reason for the shrill quality and to check the validity of Haas's conclusions when applied to sound reflected from overhead.

2. EFFECT ON MUSICAL QUALITY OF REFEXIONS WITH SHORT TIME DELAYS

2.1. Experiments Using a Magnetic Delay System

In the first of the experiments, programme material recorded in dead or reverberant surroundings was processed by the addition of a version which had been delayed by intervals up to 80 ms, using a magnetic delay system. The processed material was made into test tapes and subjects were asked to express preferences between pairs of recordings, one of each pair being the original material, and the other the original material with a delayed reflexion.

Those subjects who gave consistent answers showed an agreed preference for the original recording, and found those samples with 10 - 40 ms delayed reflexion of poorer quality. There was no further deterioration in the case of the longest delays. In this experiment both the 'original' and 'processed' samples had been re-recorded by the magnetic delay equipment, and therefore both showed some deterioration due to the additional recording process. Moreover, it might be argued that the version having the delayed reflexion would introduce more disturbing wow and flutter components, and that this was the feature disliked by the subjects.

In support of this it was noticed that deterioration was most marked in the upper string passages where one would expect undesirable combinations of flutter and vibrato to be present.

2.2. Experiments Using Two Loudspeakers in a Free-field Room

A second experiment was therefore tried, in which two loudspeakers were located about 11 feet (3·4 m) apart in Free Field Room 2, and were fed with the same programme in parallel. Subjects were seated one at a time in line with the two loudspeakers, so that the sound from the farther loudspeaker was delayed by 10 ms, and were provided with a changeover key which enabled them to cut the farther loudspeaker and apply a compensating increase of level to the nearer loudspeaker. Listening tests were made using orchestral music, speech and a violin played in Free Field Room 1. Most of the tests were made with equal levels on the two loudspeakers when they were both operating simultaneously.

These experiments showed a marked deterioration in the quality of orchestral music, particularly the string quality, and the deterioration was of the same type as has been noticed in some concert halls with reflectors. Speech became coloured with both low frequency and high frequency distortions. Violin tones also showed distortion and the bowing noise became coloured and therefore more noticeable. Some subjects thought that vibrato made these effects worse but an equal number did not.

It was also noticed that random noise from the loudspeakers became very coloured and warble tone developed a thumping sound in some conditions of loudspeaker phase. There seems to be no doubt that all these distortions can be explained as comb filter effects due to interference between the sounds from the loudspeakers.

2.3. Determination of Thresholds of Audibility of Reflexions

Further experiments were carried out to determine the levels below which the delayed sound ceased to have a noticeable effect on listening quality. The listening arrangement was the same as for the second experiment, but the difference in levels due to the far and near loudspeakers was adjustable by the experimenter outside the room. The experimenter reduced the level by steps, in response to a light signal from the subject until there was no perceptible difference in quality between the two conditions. The level at which this occurred was noted as the ‘threshold from above’. The subject then signalled the experimenter to increase the level until he could again perceive a difference in quality. This level was noted as the ‘threshold from below’.

For each subject, thresholds were determined three times with each programme source. The results are shown in Table 1.

The speech was from a recording made under free-field conditions, but all the music sources were from recordings made under reverberant conditions.

3. JUDGEMENT OF VERTICAL DIRECTION OF SOURCE

3.1. Introductory Considerations

A great deal is known about the judgement of direction of sound source in a horizontal plane, but very little about vertical directional judgements. The side to

TABLE 1

Thresholds of Perceptibility of Echoes of Delay of 10 MSEC

PROGRAMME SOURCE	THRESHOLD FROM ABOVE (dB)	STD. ERROR OF MEAN (dB)	THRESHOLD FROM BELOW (dB)	STD. ERROR OF MEAN (dB)	NO. OF SUBJECTS
Random noise with constant energy per octave band	−16·0	1·0	−14·2	1·0	15
Speech	−12·1	0·9	−10·6	0·8	16
Choral Music	− 6·2	1·0	− 4·7	0·9	13
Piano	− 4·5	0·8	− 3·2	0·8	13
String Quartet	− 4·5	0·6	− 3·2	0·6	11
Orchestral Music	− 3·7	0·7	− 2·4	0·6	11

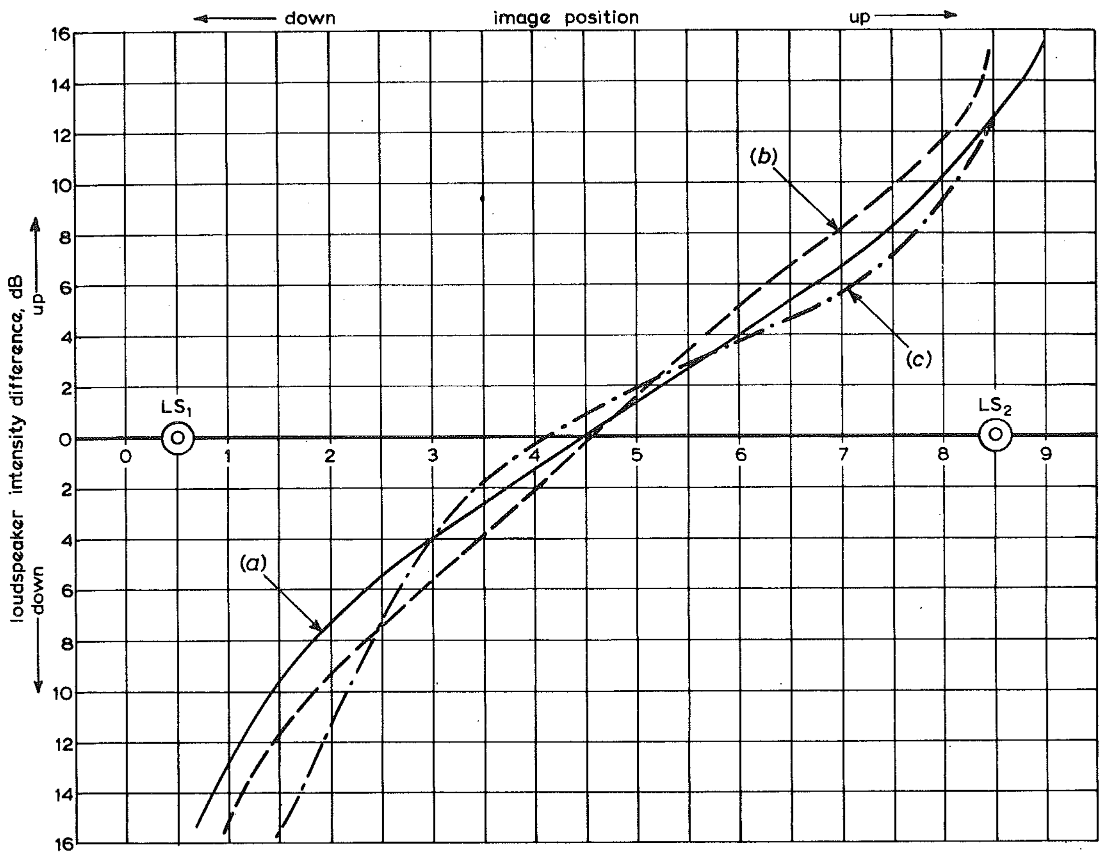

Fig. 1 - Dependence of Image position on relative intensities of two loudspeakers, one vertically above the other, equidistant from observer

(a) Subject 'a' *(b)* Subject 'b' *(c)* Subject 'c'

side symmetry of the human body makes it difficult to understand how any vertical directional sense can exist. In many individuals it is certainly less marked than the horizontal directional sense, and some individuals appear to have very little ability to judge.

Cherry[2] has stated that vertical directional judgement must be achieved by small, possibly unconscious, movements of the head, and shows that quite small angles of movement would be sufficient to give a strong directional sense. In most of our experiments, therefore, the subject's head was maintained in a fixed position by the use of a chin rest. With individuals who had a strong directional sense in the vertical plane, fixing the head position did not, however, appear to make much difference.

3.2. Localization of Real Sources in a Vertical Plane

Preliminary experiments showed that the type of test signal makes a great difference to discrimination. It was found to be virtually impossible to locate a

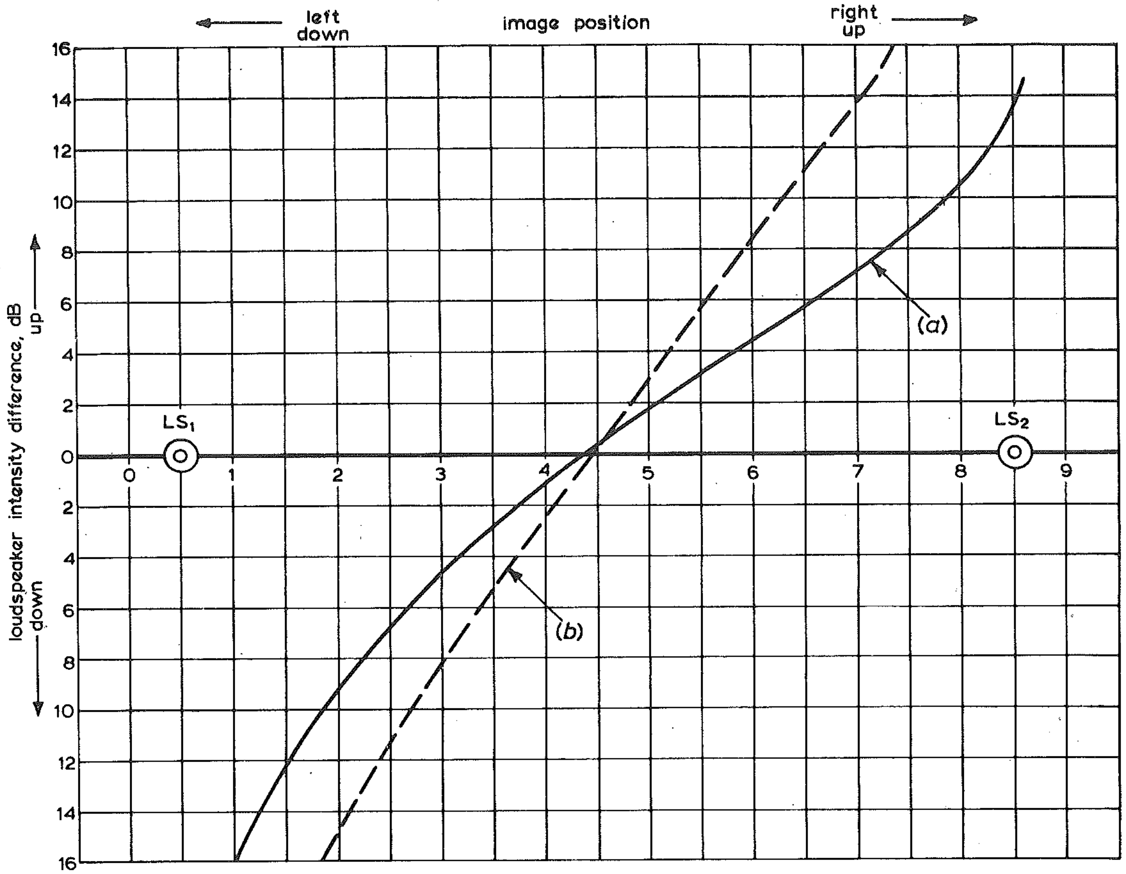

Fig. 2 - Dependence of Image position on relative intensities of two loudspeakers in vertical and horizontal relationship

(*a*) Mean of three subjects, loudspeakers in vertical plane

(*b*) Loudspeaker in horizontal plane (reproduced approximately from a paper by Leakey[3])

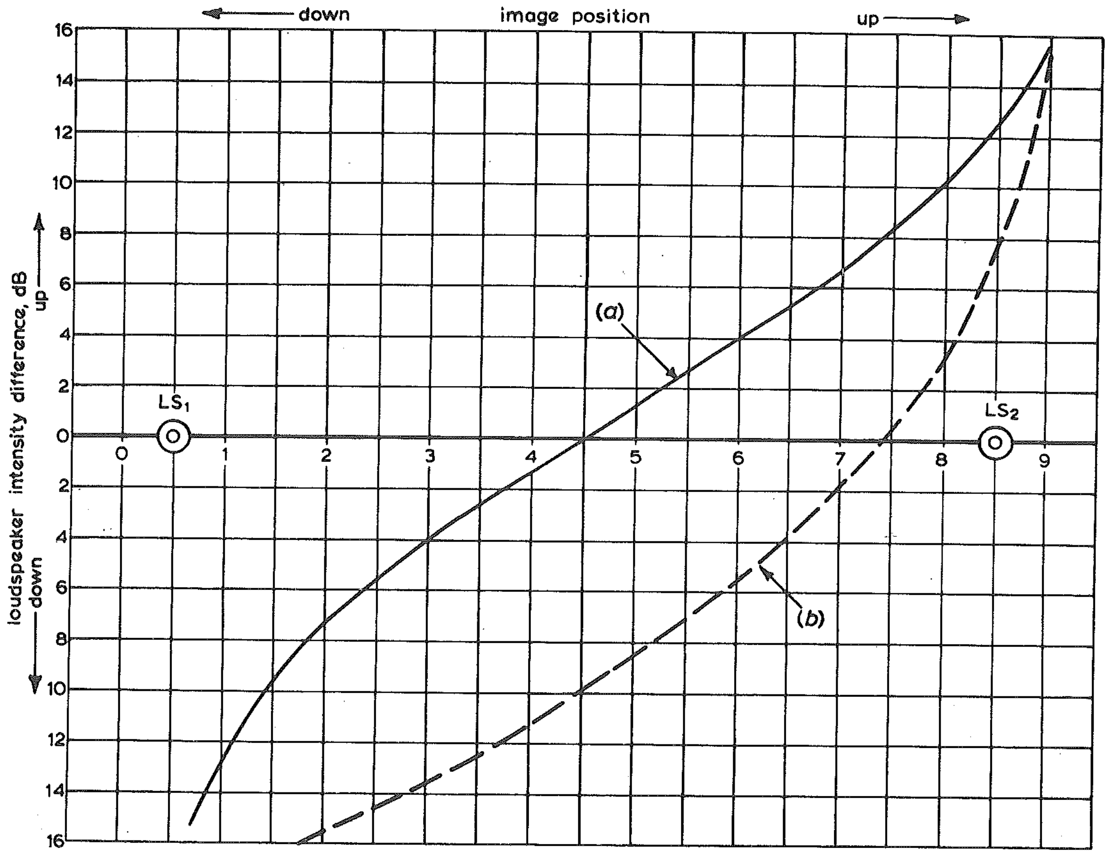

Fig. 3 - Effect on image position of time difference between loudspeakers (Subject 'a')

(a) Loudspeaker in phase *(b)* With 20 ms delay on Loudspeaker LS1

source of pure tone except by moving about the room and moving the head into different positions. A wideband sound appeared to be necessary for good vertical discrimination and hence, to obtain the most meaningful results, recorded clicks were finally chosen as the test signal. In one experiment seven identical loudspeakers were arranged in a vertical array behind a thin net screen, and subjects were asked to judge from what point on a vertical scale in front of the screen the sound appeared to come. The test signal was switched in random order to each of the seven loudspeakers in turn.

This experiment showed that fairly accurate vertical directional sense is possessed by several of the subjects, whereas others had very little directional sense. A further experiment is proposed but has not yet been carried out, in which accelerometers will be fixed to the heads of the subjects to measure the amplitude of unconscious rotary movement of the head. On Cherry's hypothesis one might expect that the subject showing best vertical directional judgement would tend to have greater head movements even when restricted by the chin rest.

3.3. Localization of Images Due to Two Sources

The subjects having good directional sense were used for the second experiment, which was designed to ascertain whether two sound sources would appear to fuse into a single source, and if so to find where the apparent source was located. Clicks were used as the test sound.

Two loudspeakers were mounted, one about 5 feet (1·5 m) above the other, behind a screen which had a vertical scale in front. The two loudspeakers were fed in parallel with an attenuator in each circuit so that the relative loudnesses could be altered. The subject was asked to name the point on the vertical scale from which the sound appeared to be issuing. Fig. 1 shows the results obtained with three different subjects. The horizontal scale shows the position of the apparent source, the lower loudspeaker being located at ½ and the top loudspeaker at 8½.

The ordinate is the calculated difference in decibels between the loudnesses of the two loudspeakers, equal loudness being on the figure 0 on the centre of the diagram. It is evident from these results that the subjects found that the two sources fused into one image, the position of which they could judge with some accuracy.

In this respect the fusion of two sources in a vertical plane behaves somewhat similarly to that in a horizontal plane. In Fig. 2, results for the horizontal plane, as found by Leakey,[3] are compared with the average of the three curves shown in Fig. 1 for the vertical plane.

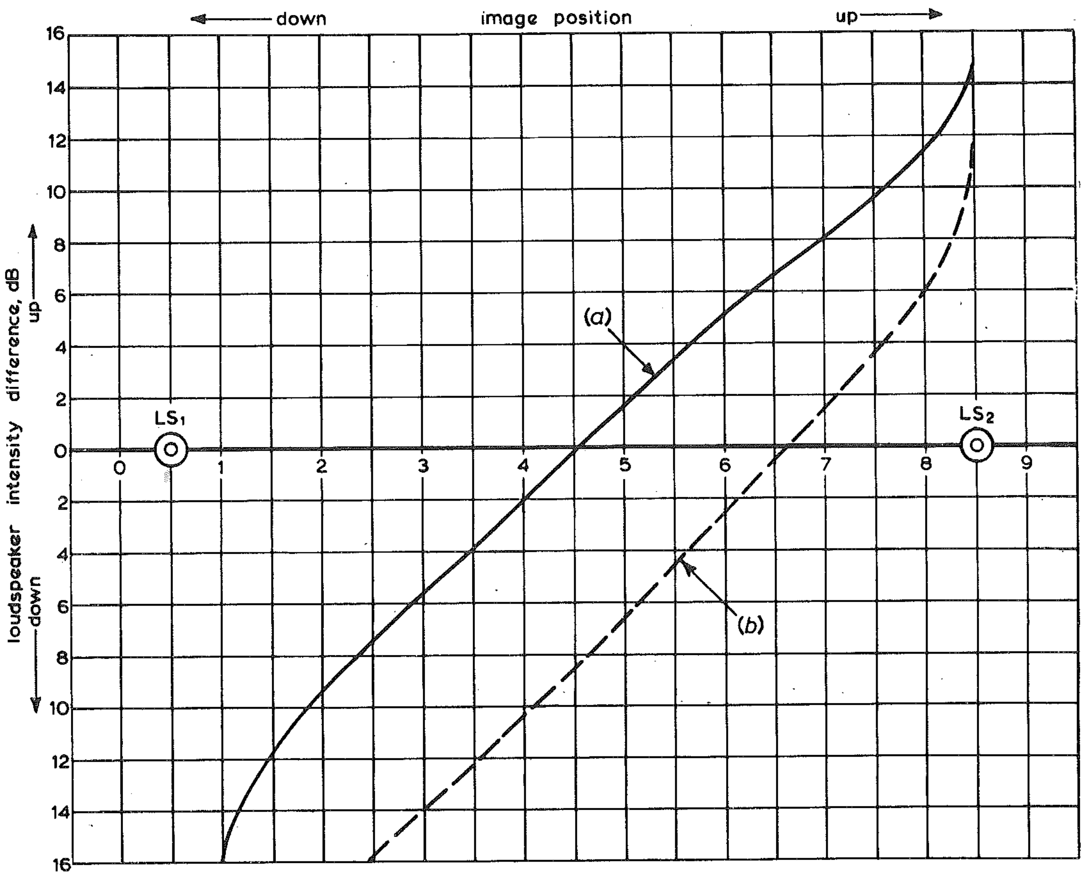

Fig. 4 - Effect on image position of time difference between loudspeakers (Subject 'b')

(a) Loudspeakers in phase *(b)* With 20 ms delay on Loudspeaker LS1

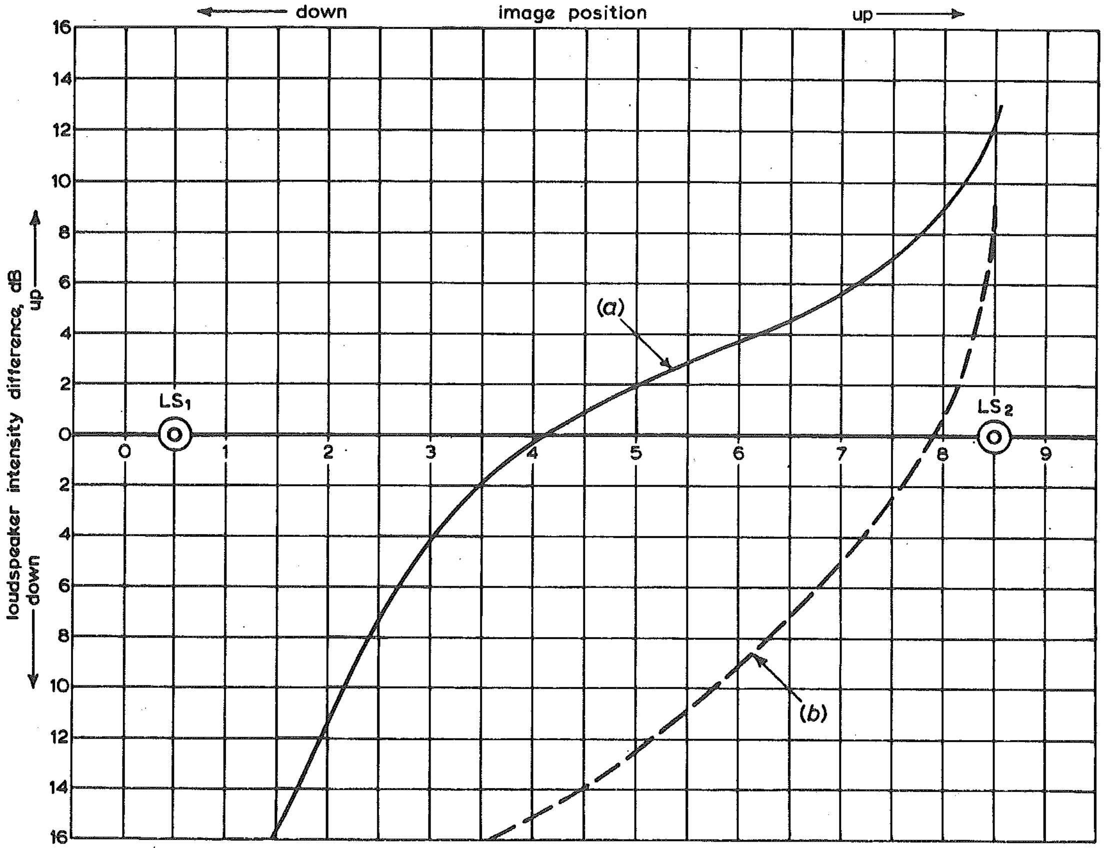

Fig. 5 - Effect on image position of time difference between loudspeakers (Subject 'c')

(a) Loudspeakers in phase *(b)* With 20 ms delay on Loudspeaker LS1

3.4. Effect of Delay of One Source on Image Position

In a third experiment one of the loudspeakers was fed with a signal delayed by 20 ms using the tape delay system, and the previous experiment was then repeated. Figs. 3, 4 and 5 show the results for the same three individuals.

It will be seen that although the position of the fused image is displaced by the delay with respect to the curves obtained with an identical signal, the movement of the image between the two sources is still continuous as the level of the delayed source increases. It is interesting to note that Haas[4] found that for the horizontal plane the image remained located on the undelayed loudspeaker until there was a level difference of about 10 dB, when the image position moved quickly to the delayed loudspeaker.

It is therefore clear that relative delay between two sources has effects in the vertical plane different from those in the horizontal plane. The results from these experiments, though requiring support by further work, indicate that with delays of the order of 10 ms to 50 ms there is a range of level differences between the direct and the reflected sound in which the fused image appears between the two

Fig. 6 - Stage of Southampton Guildhall after reconstruction, showing coffered walls and ceiling

sources. In a concert hall with a reflector this would give the effect that the sound was coming from a region above the orchestra as has been observed subjectively. This effect might well be more noticeable on the string sections of an orchestra because the direction of maximum radiation of a violin is at right angles to the plane of the instrument, and would therefore normally be in an upward direction towards the reflector; this could greatly increase the level of the reflected sound relative to the direct.

4. OTHER CONSIDERATIONS CONNECTED WITH THE REFLECTOR PHENOMENA

Some interesting results were obtained in this connexion in Southampton Guildhall where stage reconstruction was necessary after a fire. They have been previously reported[5] but are summarized here for completeness. Experiments carried out to determine the effect of a reflecting canopy left no doubt that the canopy produced a shrill quality normally noticed in these circumstances. During reconstruction the entire back wall and ceiling of the stage were broken up into rectangular diffusing shapes as shown in Fig. 6. Pulse echograms before and after reconstruction are shown in Figures 7(*a*) and 7(*b*). The large fluctuations in Fig. 7(*a*) do not appear in the diffused conditions under which Fig. 7(*b*) were taken.

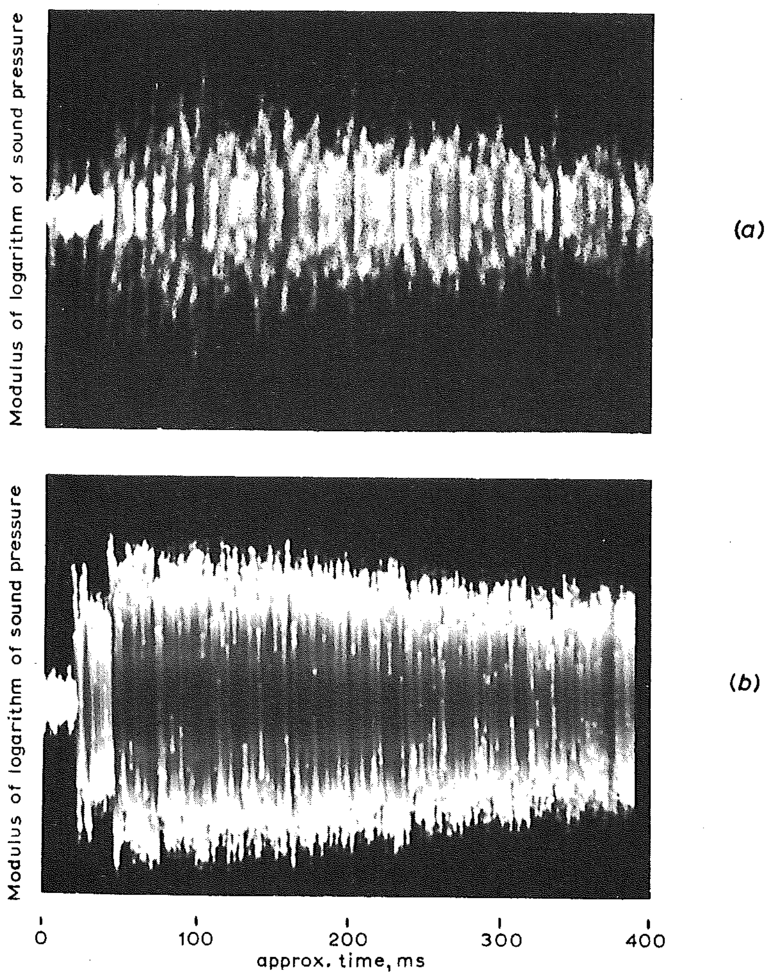

Fig. 7 - Short-pulse echograms near front of Southampton Guildhall (loudspeaker on stage)

(a) Before reconstruction
(b) After reconstruction

The increase in loudness in the rear seats was measured with and without reflectors as has already been done in measurements in several concert halls.[6] The reflectors in the Southampton Guildhall produced an average of 1·4 dB level increase at the back, and this was accompanied by the shrill quality already mentioned. However, actual loudness may not be the most important subjective quality. Beranek[7] believes that strong first reflexions are necessary to give greater intimacy, but his experiences with the Philharmonic Hall in New York indicate that increase of intimacy may be carried too far because the tonal quality becomes unpleasant for most listeners. It seems probable that an audience listening in a large modern hall prefers a smooth reverberant sound to the shrill quality produced by strong first reflexions.

5. CONCLUSIONS

Preliminary experiments described in this report were carried out to investigate the mechanism whereby large canopies and reflectors in studios and concert halls produce the subjective effect of shrill tonal quality. This is shown to be due to interference effects between the direct sound and that due to a strong reflexion from a canopy or other reflector.

It is also shown that the precedence effect investigated by Haas for the horizontal plane does not apply to the vertical plane and consequently the sound from an orchestra may appear to come from above the performers when there is a large canopy overhead.

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Printed by BBC Research Department, Kingswood Warren, Tadworth, Surrey